

A Thermal Precipitator for Fire Characterization Research

Marit Meyer, NASA Glenn Research Center

Vicky Bryg, National Center for Space Exploration Research (NSCER), Microscopy

Outline

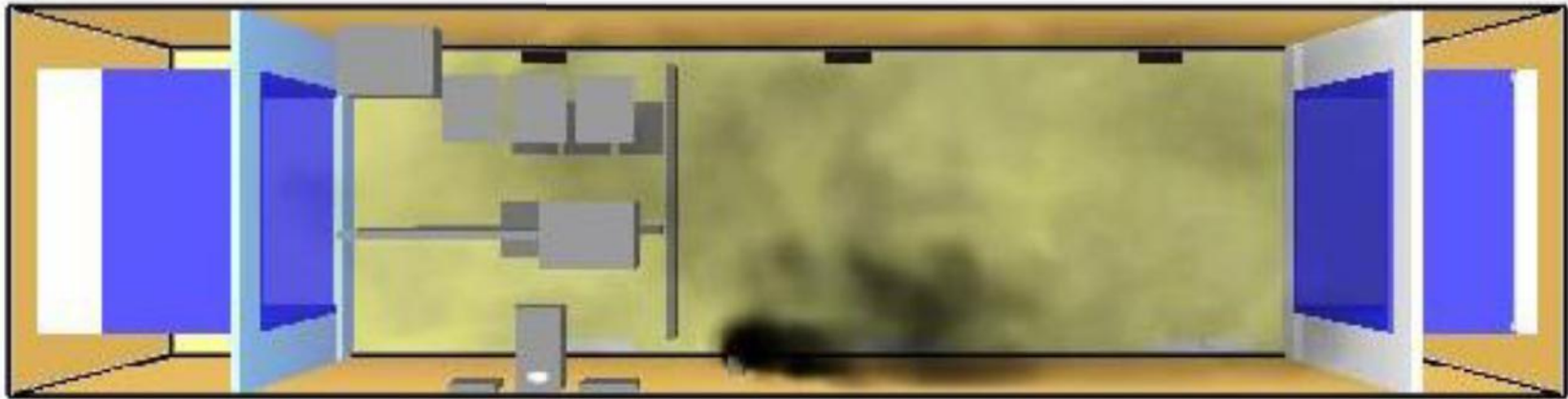
- Motivation – Fire Characterization Research
- Background
- Design goals
- Modeling
- Testing & Hardware
- Results
- Conclusion

Fire Characterization Research

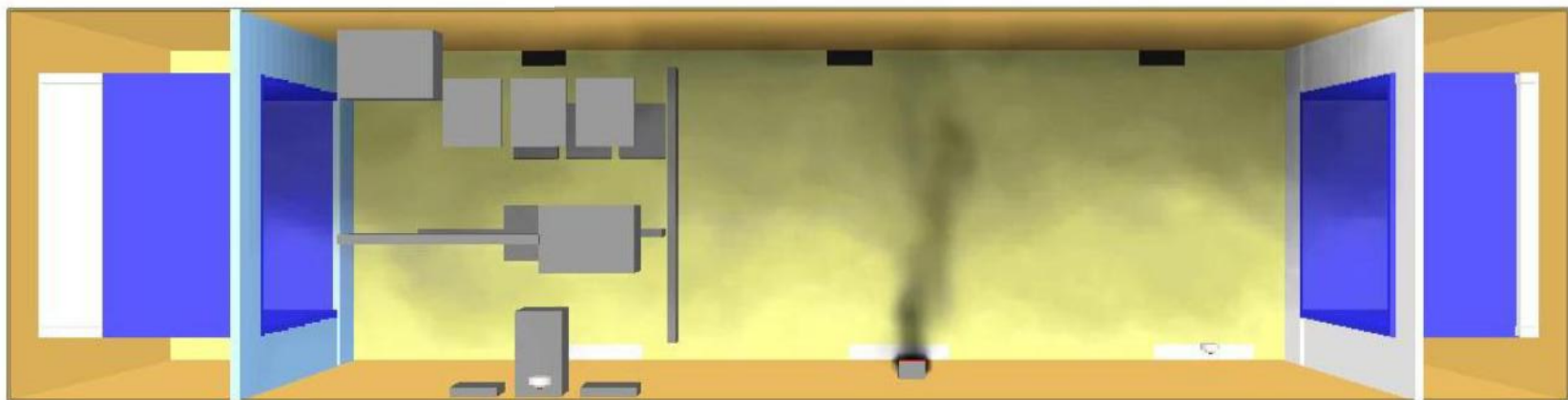
at NASA Glenn Research Center

- Most likely source of a fire on the International Space Station is overheating electronic equipment
- Early detection (before flame develops) allows rapid crew response
- Spacecraft fire safety is unique
 - No natural convection to concentrate smoke at ceiling
 - Smoke generated will disperse slowly through the cabin by forced convection caused by the ventilation flow
 - Approximately 10-15 cm/s but depends on location, stowage, etc.

ISS Destiny Smoke Detection Simulation-25% Soot



Low-gravity



Normal-gravity

Fire Characterization Research

- Next-generation space fire detectors will consist of
 - Aerosol sensors
 - Gas sensors
- } Appropriate alarm thresholds
will minimize false alarms
- Multiple small, low-power sensors will allow distributed detectors and more rapid fire response

Fire Characterization Research

- Need: Characterize aerosols and gases produced by overheating common spacecraft materials
- A thermal precipitator was designed to collect smoke aerosol particles for microscopic analysis
- Information on particle morphology, size and agglomerate structure supplements other aerosol and gas data obtained in fire research

Fire Characterization Research

- Test smoke
 - Kapton, Teflon, circuit board, wire insulation, Nomex
 - 300° C to 640° C
 - 1×10^5 to 1×10^6 particles/cm³
 - 40 to 70 mg/m³
 - $100 \text{ nm} < d_p < 1000 \text{ nm}$

Fire Characterization Research

- Goal is to characterize smoke
- Verify a repeatable fire challenge for testing
 - Aerosol instruments
 - Gas sensors
 - Post-fire clean-up equipment
- Multiple NASA smoke test facilities
 - Slightly different burn methods
 - Check fuel preparation consistency

Thermophoresis

- Thermophoretic force, F_{th} , on a particle is the result of a temperature gradient established in the gas medium
 - The force is in the direction of decreasing temperature
- For small particles (large Knudsen number) thermophoresis is explained by kinetic theory of gases
- In the transition and continuum regimes, Navier Stokes equations with slip-corrected boundary conditions have been used

Thermophoresis

- The thermophoretic force on an aerosol particle can be expressed as *(Brock, 1962)*

$$F_{th} = \frac{-6\pi\mu v d_p C_s \left(\frac{k_a}{k_p} + C_t Kn \right) \frac{\nabla T}{T}}{(1 + 3C_m Kn) \left(1 + 2\frac{k_a}{k_p} + 2C_t Kn \right)}$$

μ = viscosity of air

v = kinematic viscosity

d_p = particle diameter

k_p = particle thermal conductivity

k_a = air thermal conductivity

Kn = Knudsen number, $2\lambda / d_p$

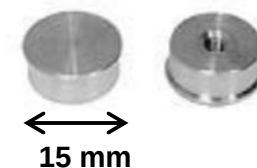
∇T = Temperature gradient

T = Absolute temperature of particle

$C_t = 2.18$, $C_m = 1.14$, $C_s = 1.17$, thermal exchange coefficients *(Talbot et al., 1980)*

Design

- Develop a portable device for sampling smoke aerosol particles for microscopy
- Collect particles on easily inserted substrates for microscopy
 - Scanning Electron Microscope (SEM) aluminum specimen mount
 - Hitachi stubs with threaded hole
 - Transmission Electron Microscope (TEM) grid
 - Attach to aluminum stub with carbon tape



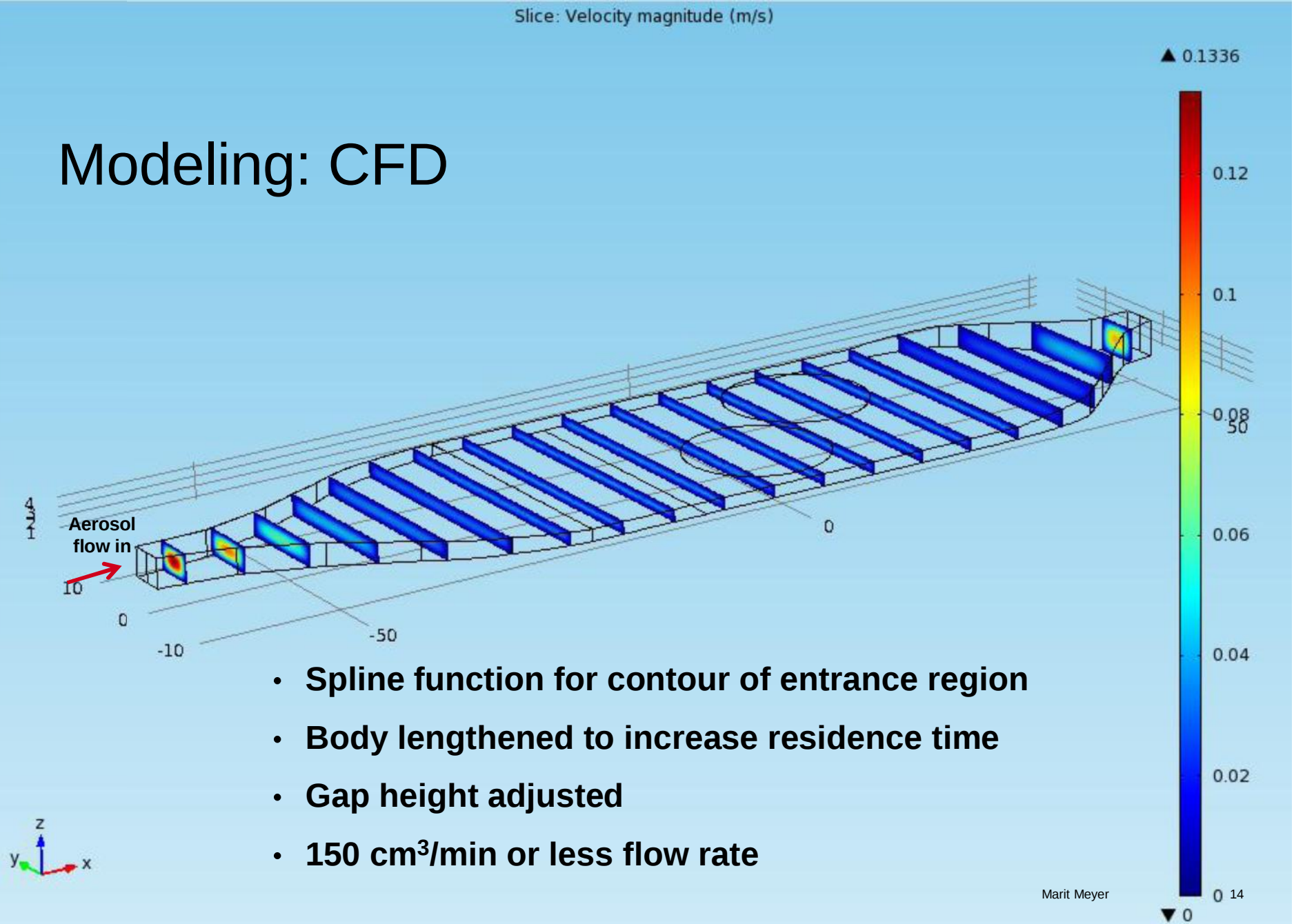
Design

- Reduce aerosol flow from ¼" tubing inlet to very narrow gap
 - Laminar flow
- Highest possible temperature gradient achievable with minimal thermal management (power, size)
 - Thermoelectric coolers (TE)

Design

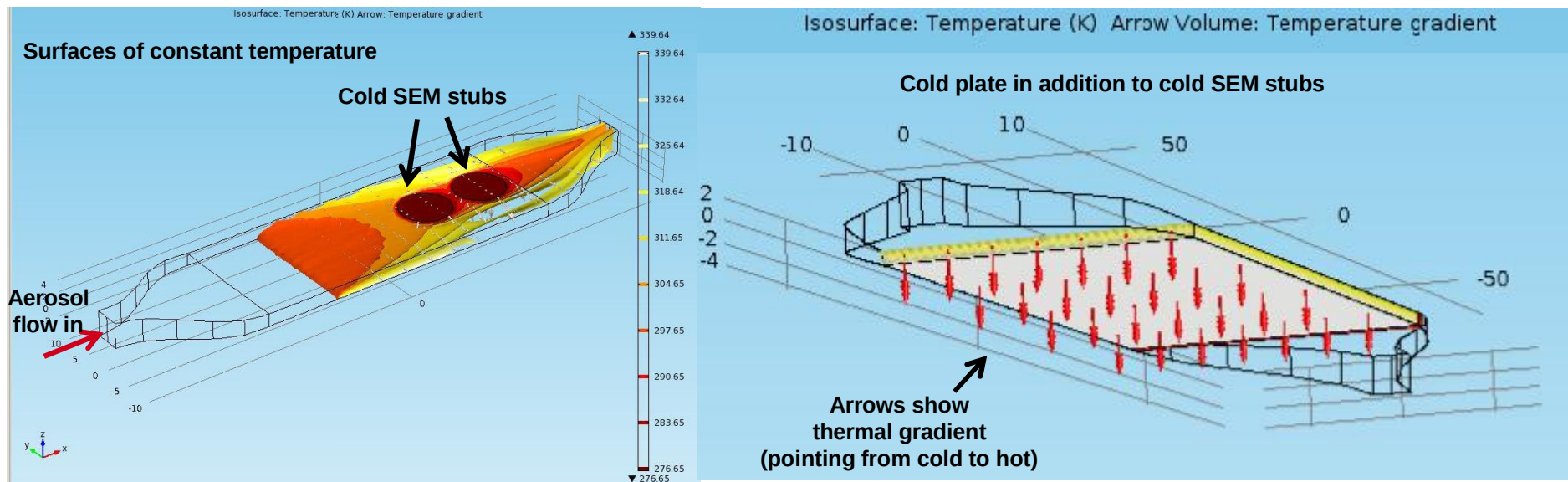
- Particle residence time in TP is controlled by
 - Flow rate
 - Height of gap
 - Length of body
 - Temperature gradient
- Multiphysics finite element model determined reasonable combination of these variables
 - Computational Fluid dynamics
 - Thermal
 - Particle trajectories

Modeling: CFD



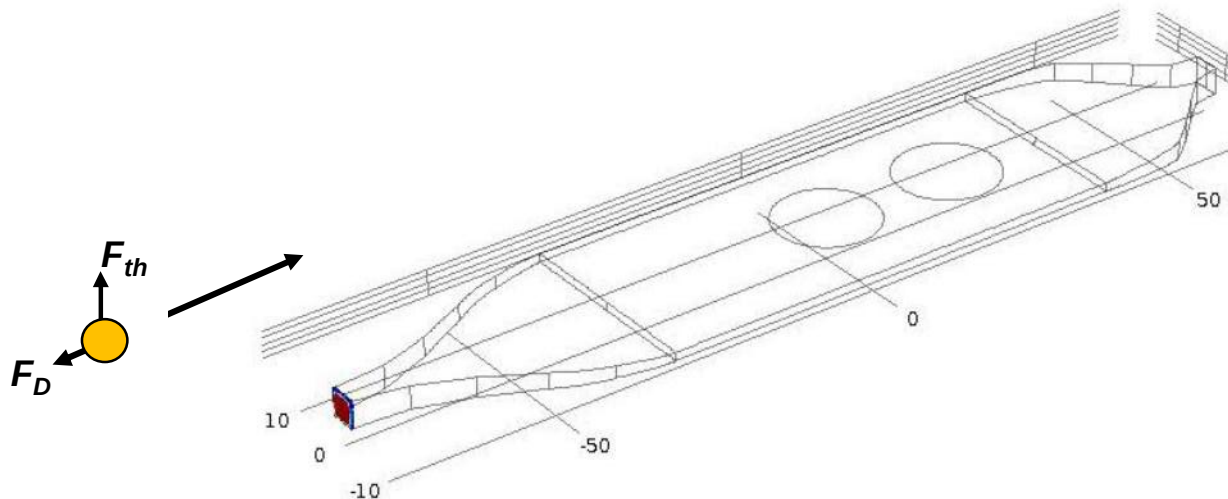
Modeling: Thermal

- Design iteration from model results
 - Increased area of constant thermal gradient



Modeling: Trajectories

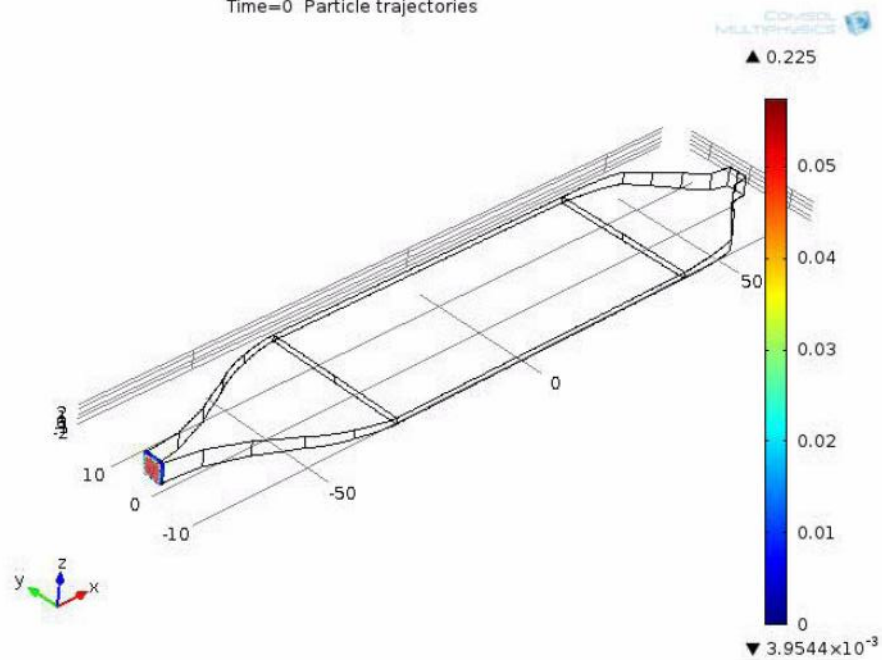
- Particle trajectories based on combined physics in numerical model
 - Slip-corrected Stokes drag and thermophoretic force
 - Average value of particle thermal conductivity 0.19 W/m-K
 - Multiple particle sizes: 100 nm, 500 nm, 1000 nm



Modeling: Trajectories

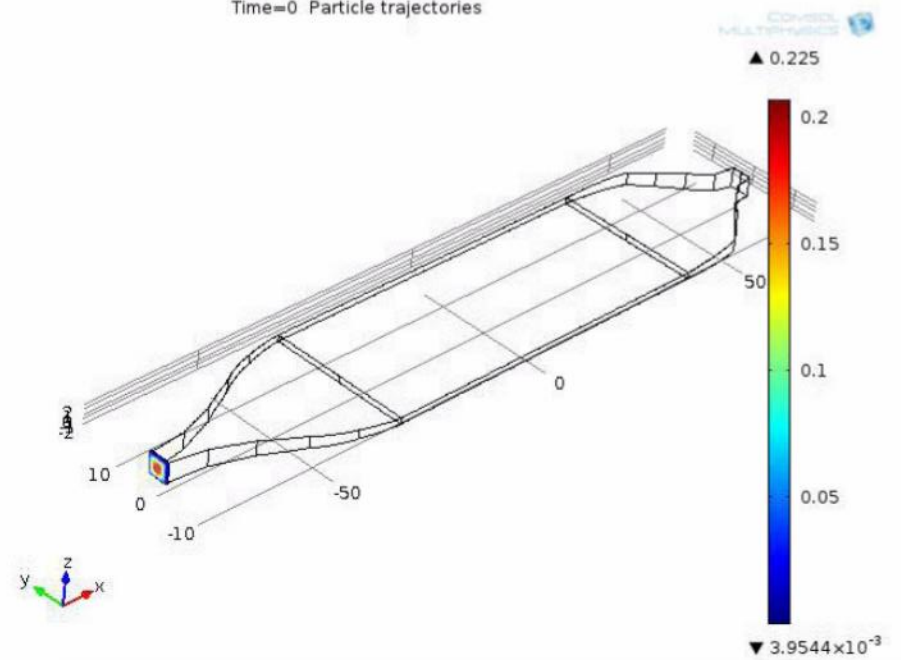
100 nm particles

Time=0 Particle trajectories



1000 nm particles

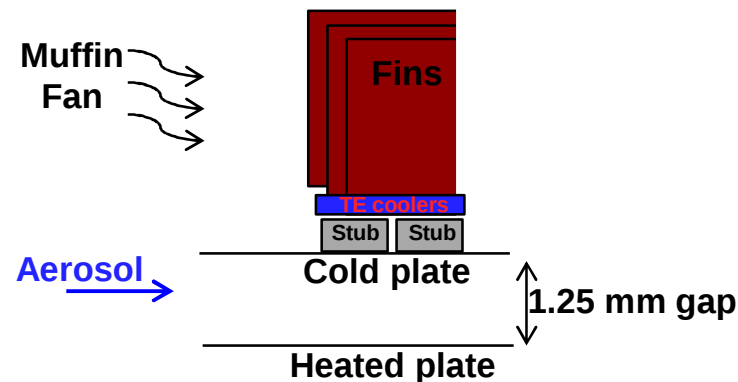
Time=0 Particle trajectories



- SEM stub locations
- Final flow rate

Hardware

- Thermoelectric (TE) coolers and Kapton heater provided temperature gradient
 - Gap height 1.25 mm
 - No direct temperature control, only ΔT of cooler
 - Efficiency of heat removal from the hot side of the TE cooler established the gradient



Thermal Design Iterations During Testing

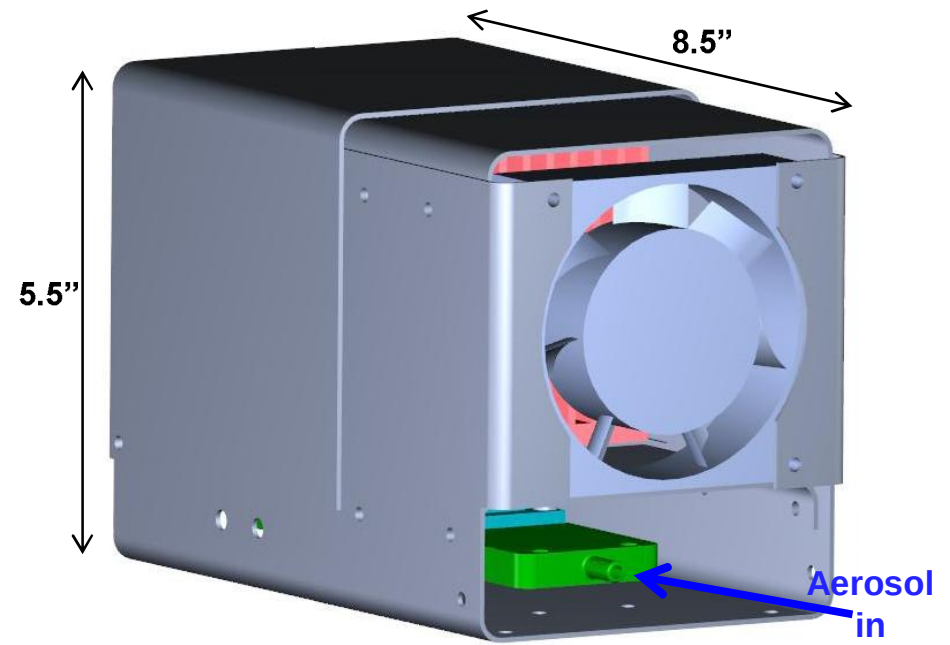
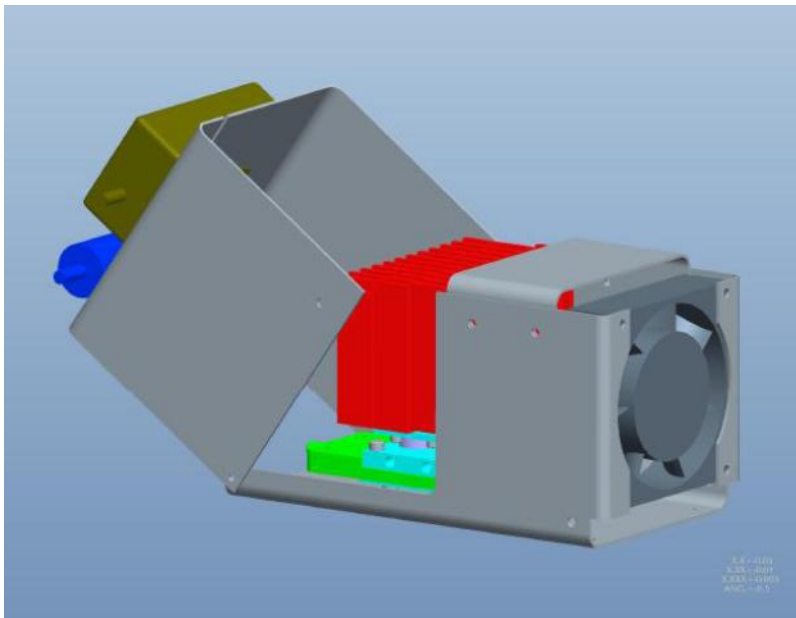
- Permanent thermocouples on cold plate and heated plate
- Improve heat removal from TE cooler
 - Larger fin surface area & larger fan
- Increase contact conductance between stubs, TE coolers and heat sinks
- Add insulation

Testing

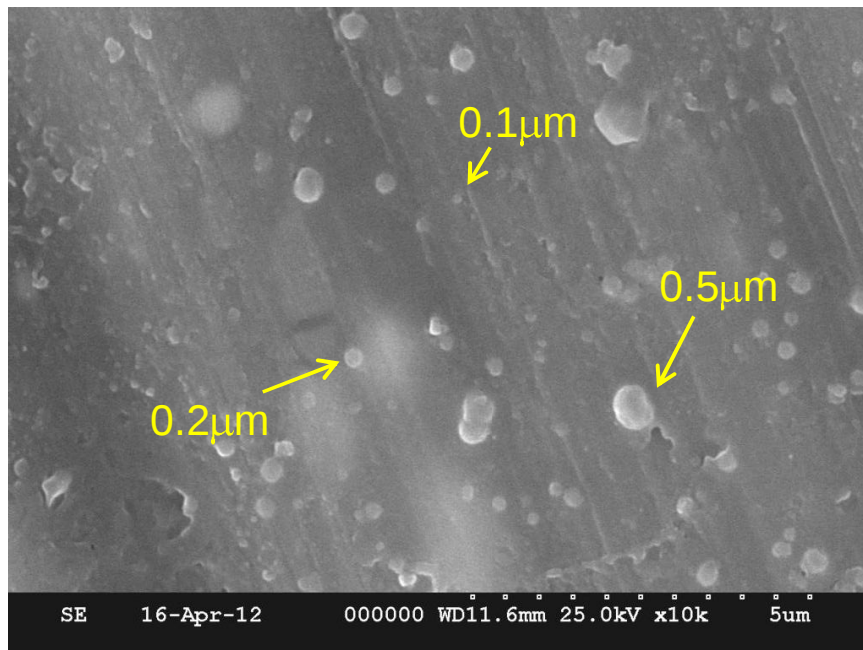
- Achieved 70° C temperature gradient with 8 to 10 minute warm-up time
 - Heated plate ~ 65° C
 - Cold plate ~ -5° C
- Sampled filtered air with TP for an hour
 - Verified no particles on stubs
- Verified PSL particle collection
 - 1.0, 0.67 μm and 100 nm
- Condensation issues during testing with PSL aerosol generation from aqueous solution
 - Smoke chamber dew point ranges from -9° to -18° C

Packaging

- Aluminum housing positions fan and directs air onto heatsink for heat removal
- Lid opens for access to SEM stubs

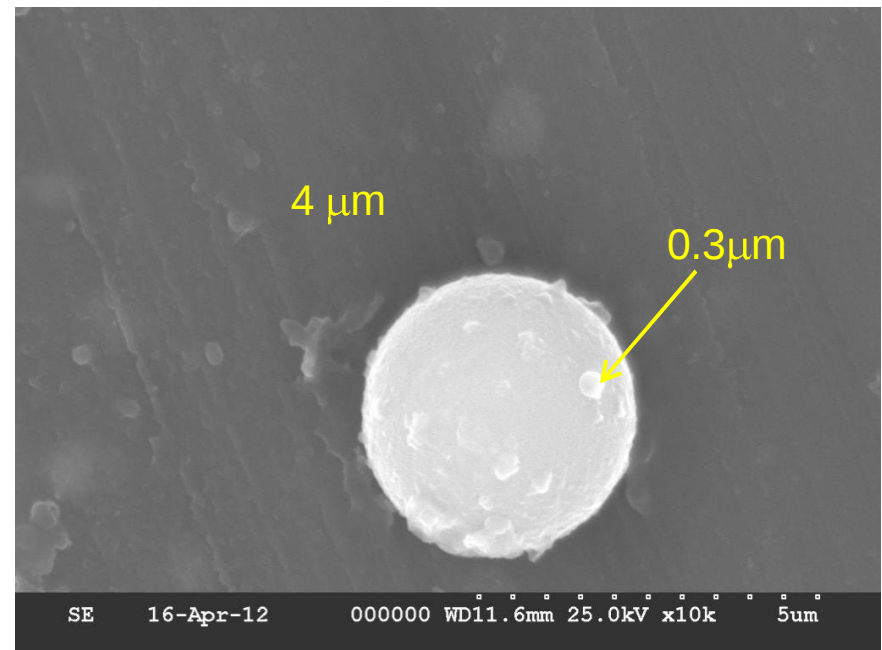


Wire Insulation 640° C



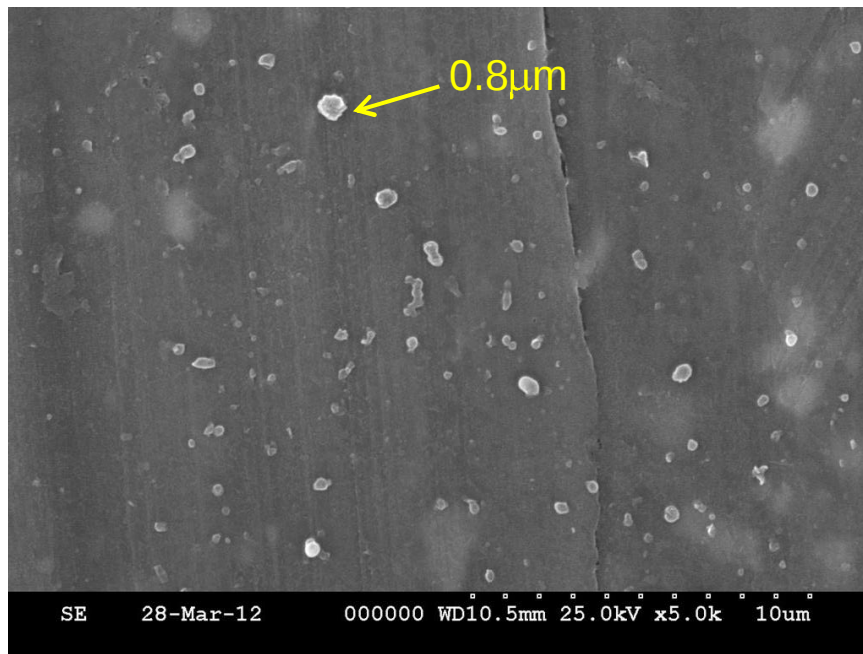
SEM stub

— 1 μm



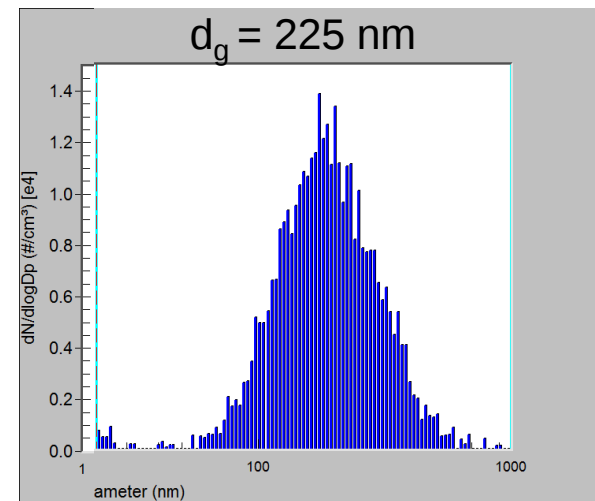
— 1 μm

Kapton 640° C

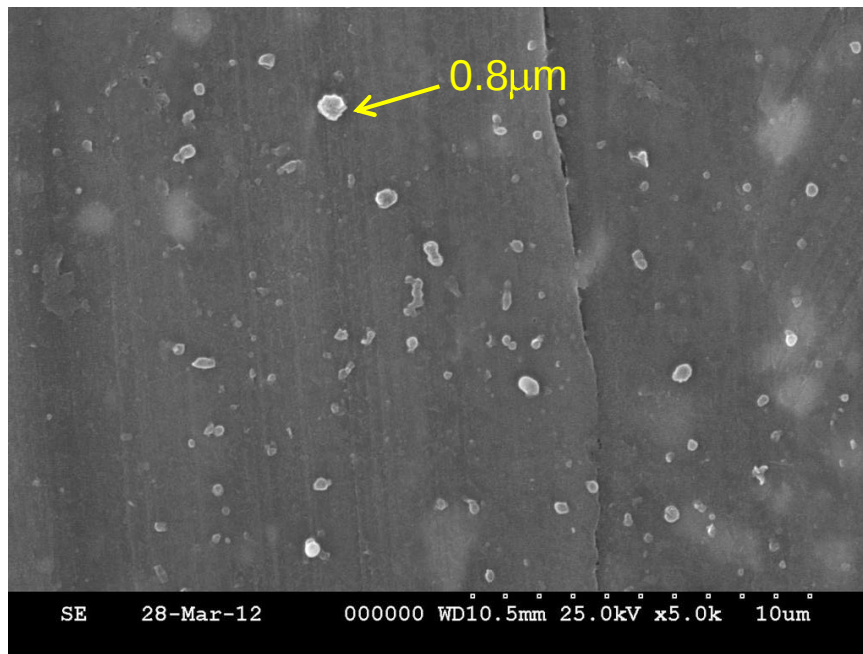


SEM stub

— 2 μm

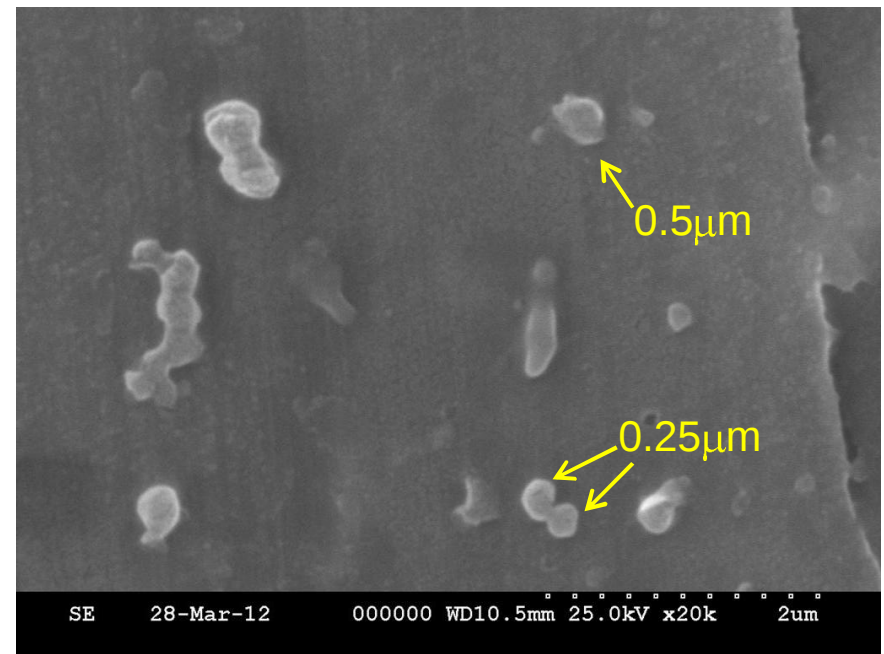


Kapton 640° C



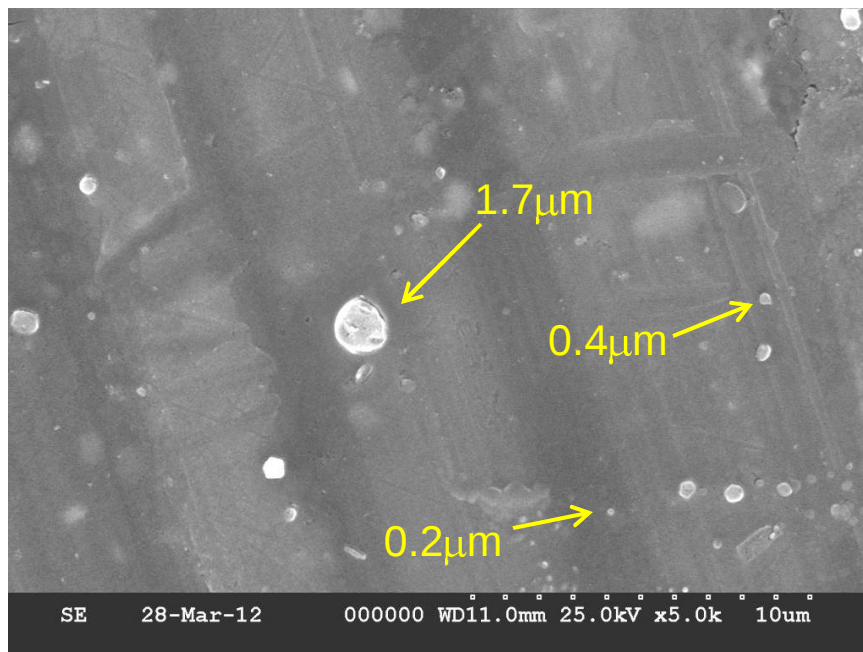
SEM stub

— 2 μm



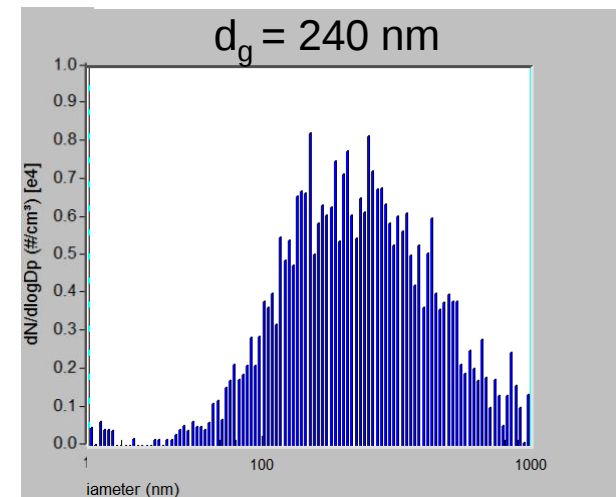
— 1 μm

Teflon 640° C

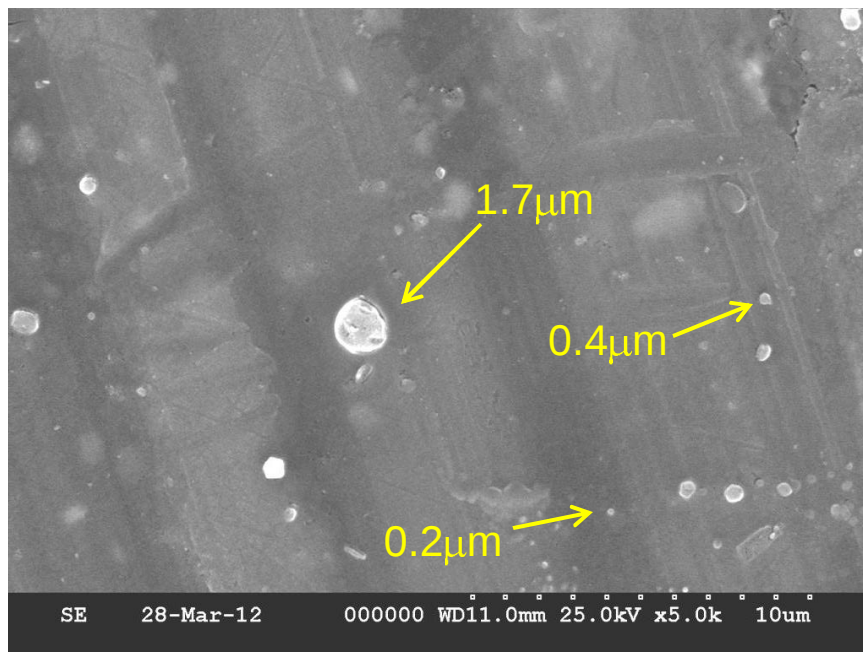


SEM stub

— 2 μm

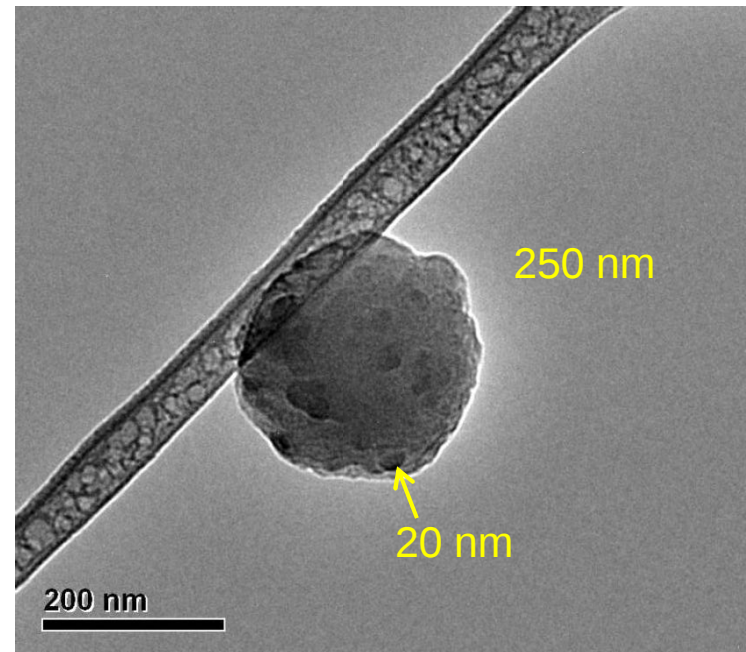


Teflon 640° C



SEM stub

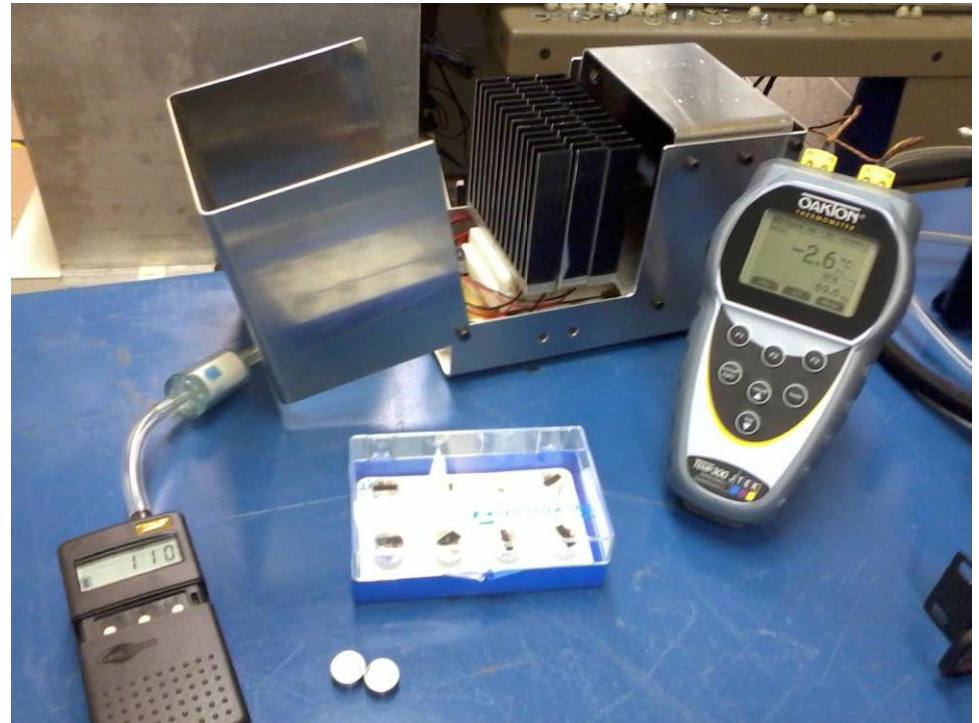
— 2 μm

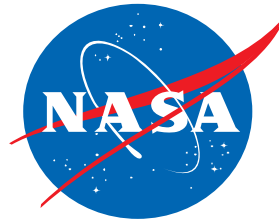


TEM grid

Conclusion

- Thermal precipitator designed, modeled and tested
- Successful particle collection
- Fire characterization research ongoing
 - Aerosol/gas kinetics

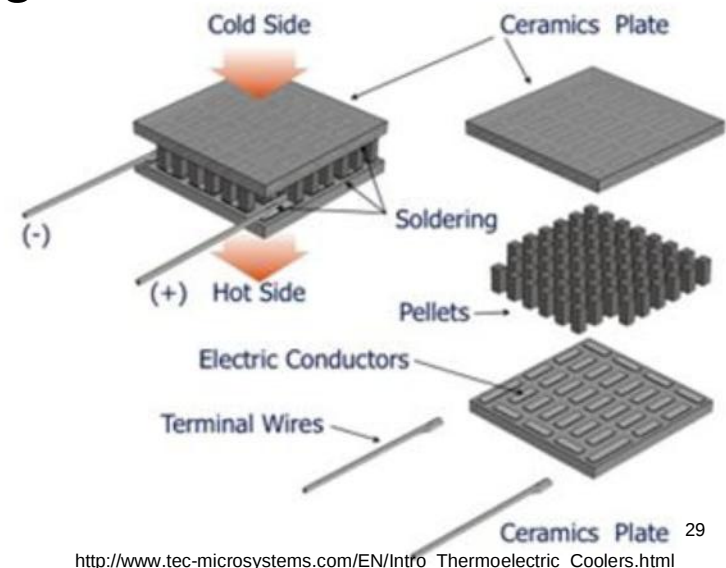




Acknowledgment: Daniel Gotti contributed to the mechanical design and did the CAD model for this project

Backup Slide: Thermoelectric Cooler

- Also known as Peltier cooler or heater
- Creates a heat flux between the junction of two different types of materials (N and P-type semiconductor pellets)
- Datasheet gives $\Delta T_{\max}$ (between each side of cooler), cooling capacity, current and voltage restrictions



Backup Slide

- Carbon tape strip placed in the direction of flow
- TEM and HRTEM grids are attached to carbon tape



Backup Slide

